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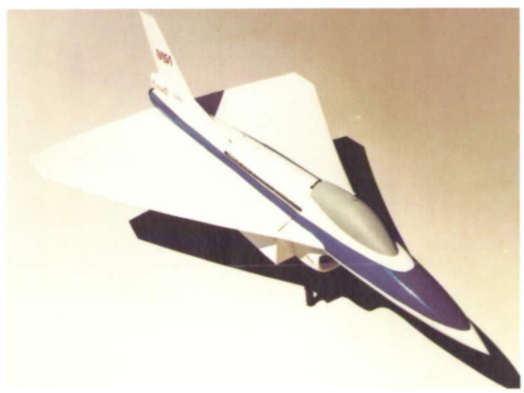
POWERED-LIFT AIRCRAFT TECHNOLOGY



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POWERED-LIFT AIRCRAFT TECHNOLOGY

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INTRODUCTION

Powered-lift aircraft have the capability to vary, in flight, the direction of the force produced by the propulsion system. Propulsive force is a vector, not a scalar quantity. The magnitude and the direction of the propulsive force is varied to produce thrust, lift, or various thrust/lift components. The propulsion system and airframe are integrated, or closely coupled, so that in all or some flight modes, propulsion-system exhaust flows influence the external aerodynamics about the airframe. Frequently, but not always, powered-lift aircraft have aircraft flight control systems augmented by propulsion systems.

For over 30 years powered-lift research and technology (R&T) has been perceived in the context of enabling an aircraft to operate from short or reduced-length runways, or from minimum-size terminal sites. Powered-lift aircraft have been categorized by such acronyms as STOL (for short takeoff and landing) and VTOL (for vertical takeoff and landing). These acronyms correspond to the aircraft's operational capabilities at the terminal site.

Operation from small sites or reduced runway lengths is an important attribute of an aircraft, as evidenced by rotorcraft, the Harrier aircraft, and powered-lift transports such as the C-17. The powered-lift technology which enables STOL or VTOL also provides enhanced in-flight performance, such as steep-gradient flight for noise abatement and improved combat maneuverability. For these reasons, powered-lift R&T will continue to address STOL and VTOL aircraft and their associated in-flight advantages.

Today, powered-lift technology is on the threshold of expansion. Powered-lift technology may be applicable to many types of aircraft (including those without STOL or VTOL), such as subsonic transports and business jets that operate from today's long runways. For many types of aircraft, a desired set of the aircraft's parameters of merit (e.g., useful load, gross weight, noise, maneuverability) can be enhanced by applying powered-lift technology. For mission requirements that do not include STOL or VTOL, a question to address is, "Which is better, the optimally designed powered-lift aircraft or the optimally designed nonpowered-lift aircraft?" For mission requirements that do include STOL or VTOL, that question is already answered.

This report presents an overview of four categories of powered-lift aircraft:

1. Subsonic STOL aircraft
2. Subsonic vertical/short takeoff and landing (V/STOL) aircraft
3. Supersonic STOL aircraft
4. Supersonic short takeoff and vertical landing (STOVL) aircraft

Examples of research are discussed which indicate that powered-lift technology may also yield the best design for some conventional takeoff and landing (CTOL) aircraft that operate from long runways only.

Overall aircraft configurational aspects and flight controls are discussed as are aerodynamics. Propulsion systems and aircraft structures, particularly for aircraft capable of vertical flight, are of critical importance. (A current discussion of propulsion can be found in references 1 and 2.)

Structures technology applies to all aircraft. Powered-lift aircraft become increasingly competitive with nonpowered-lift aircraft as structures are strengthened and are manufactured of lightweight materials. Excellent articles are available on advanced lightweight structures, but we have not searched the literature for such references dealing with lightweight structures specifically for powered-lift aircraft.

ORIGINAL PAGE
COLOR PHOTOGRAPH

NASA's Quiet Short-Haul Research Aircraft (QSRA) landing on the U.S.S. Kitty Hawk aircraft carrier without the use of the carrier's arresting gear.

SUBSONIC STOL AIRCRAFT

Subsonic STOL aircraft discussed here have medium-to-high wing loadings and powered-lift features such as engines that are mechanically or pneumatically interconnected, wing trailing-edge flaps that are blown by engine bleed air or engine exhaust flows, and power-augmented aircraft flight controls. Not included in the discussion are the relatively lower-speed, subsonic STOL aircraft that have low wing loadings and "conventional" high-lift devices such as wing slots and unblown mechanical flaps.

Because we are unaware of military or commercial interest in single-engine, powered-lift, subsonic STOL aircraft, this discussion is limited to multiengine aircraft.

The word "short" in STOL cannot be defined quantitatively; the term is relative, meaning shorter than that required by nonpowered-lift aircraft. A 4000-ft runway is short compared to an 8000-ft runway. Powered-lift, subsonic STOL aircraft can be designed for a commercial runway as short as about 1000 ft, but not much less than that. The design requirement for a 500-ft commercial runway is so demanding, requiring very-low-speed flight capability, that a conceptual STOL design tends to evolve into a STOVL or V/STOL design.

Because of their special design, STOL aircraft have enhanced in-flight capabilities that include steep-gradient and curved-flight departures and approaches, high rates of climb, steep final descents, high maneuverability, rapid response for aborted landing, and low landing-approach airspeeds. These characteristics yield aircraft that (1) require less airspace in the near-terminal area, (2) require less ground space at the terminal, (3) operate in these smaller spaces relatively quietly, (4) have improved crashworthiness and survivability because of their low-speed capability at near-level fuselage attitudes, and (5) when equipped with modern avionics, can operate in very low visibility in adverse weather.

Civil opportunities for subsonic STOL aircraft include

1. Enhancing operations at existing terminals by using presently unused airspace and operating from separate short runways; when only long runways can be used, by complying with noise regulations, minimizing time on the runway, reducing number of landing aborts, etc.; and by operating from presently underutilized small terminals.
2. Minimizing the cost of new terminals, which is a prerequisite to transportation in many inaccessible areas in the world, and enabling new terminals through public acceptance of the aircraft's "good-neighbor" characteristics.
3. Stimulating growth in new modes such as high-speed air transportation directly to and from corporate headquarters and factories.

Military opportunities include (1) supply at more desirable distribution sites, (2) operations from partially damaged runways, and (3) enhanced operations from aircraft carriers.

Several subsonic STOL aircraft concepts are listed in table 1. There are no subsonic STOL production transports; however, the Air Force/McDonnell Douglas C-17 is in full-scale development. The powered-lift concept on the C-17 is the externally blown flap (EBF) that evolved from the YC-15 advanced, medium-STOL transport prototype. The EBF is a double-slotted, wing-training-edge flap. Lift augmentation is achieved by deflecting the flap into the exhaust from engines mounted under the wing (see figure 1-1). One advantage of this powered-lift concept is that a clean configuration for cruise flight is easily obtained by retracting the EBF. For some of the other subsonic STOL concepts,

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an efficient cruise configuration is attained with more difficulty or with a technology that is relatively unproven.

STOL concepts investigated in recent R&T activity include the augmentor wing and the upper surface blown (USB) flap. Other concepts that may be promising, such as that of a propfan STOL, are yet to be examined.

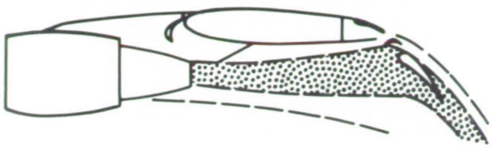
Augmentor wing R&T investigations have included a joint program with NASA; the Canadian Department of Industry, Trade, and Commerce; Boeing; deHavilland; and Rolls-Royce that has included about 1000 hr of flight research with the modified Buffalo augmentor wing research aircraft (refs. 3 and 4). The augmentor wing concept features thrust augmentation by ejecting fan bleed air between the upper and lower flap segments of the wing (see figure 1-1). The concept features "crossover" ducting of some of the fan air to the opposite wing such that rolling moments before and after engine failure are about the same. The concept is a promising one, particularly for a two-engine configuration having high STOL performance and a high subsonic cruise Mach number. For high levels of STOL performance, competing two-engine concepts require a mechanical interconnection between the two-engines, or crossover pneumatic features similar to those in the augmentor wing concept, or very powerful roll and yaw controls in the low-speed, powered-lift regime.

TABLE 1.– SUBSONIC STOL AIRCRAFT CONCEPTS

Concept	Example aircraft	Comment
Rotorcraft	None	Design studies; small step from STOL to V/STOL.
Propeller-driven		
Today's propeller	Breguet 941, NC-130B, NASA/Army OV-10A rotating-cylinder flap	Little ongoing R&T.
Advanced (propfan, unducted fan, etc.)	None	Possible promising new STOL concept.
Turbine-powered		
Augmentor wing (AW)	NASA/Canada AW Buffalo	Continuing R&T.
Circulation-control wing (CCW)	A-6 STOL	USB/CCW static tests on QSRA.
Externally blown flap (EBF)	YC-15	C-17 to be first subsonic STOL production transport.
Internally blown flap (IBF)	None	Large-scale wind tunnel model.
Jet flap	Hunting 126	Little ongoing R&T.
Lift fan	None	Large-scale wind tunnel models.
Upper-surface-blown (USB) flap	YC-14, AN-72, NASA QSRA	Continuing QSRA flight research.

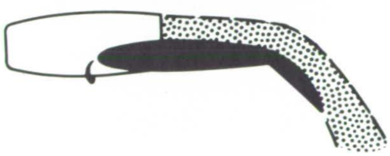
C-17

EXTERNALLY BLOWN FLAP



YC-14

UPPER SURFACE BLOWING



AUGMENTOR WING RESEARCH AIRCRAFT

AUGMENTOR WING

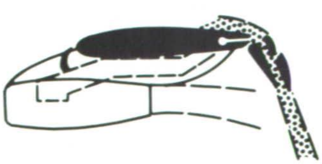


Figure 1-1.– *Subsonic STOL aircraft with schematic drawings of the powered-lift design approach. (a) Air Force / Douglas C-17, (b) Air Force / Boeing YC-14, (c) NASA / Canadian augmentor-wing research aircraft.*

The number of engines appropriate for a subsonic STOL transport is both mission-dependent and debatable. There are many options—two independent engines, two interconnected engines, three engines with several design variants, and four engines. For the USB transport design that has a high level of powered lift, there are advantages to four engine configurations, which include (1) better engine-out STOL performance at equal, all-engine, thrust-to-weight ratios; (2) efficiency gains through the use of a lower thrust-to-weight ratio on the premise of an equal engine-out effective thrust-to-weight ratio; (3) minimum engine-out roll/yaw upsets in the powered-lift regime; (4) capability for safe engine-out ferry from an austere site to a repair facility; and (5) compared to configurations with two or three independent engines, lower minimum-control airspeeds (ref. 5).

Much of NASA's recent R&T effort for subsonic STOL aircraft has addressed the USB flap concept, and NASA and the Navy have explored a hybrid concept that combines USB with the circulation control wing (CCW) concept (ref. 6). USB flaps were first explored in flight on the Air Force/Boeing two-engine YC-14 prototype (see figure 1-1). Present NASA activities include flight research with the four-engine quiet short-haul research aircraft (QSRA).

Powered-lift on the QSRA is achieved by installing four engines over the forward portion of the wing. Flared mixing nozzles direct the engine exhaust over the wing's upper surface. Air adhering to the surface of the wing continues downward over a curved flap, vectoring a portion of the propulsive force into propulsive lift. Lift is further increased by wing circulation lift caused by the high-speed air over the wing.

The QSRA has a high level of STOL performance. As one example, the commercial field length of the QSRA is 1320 ft (for sea level, standard-day, no-wind, 35-ft obstacle height, and a wing loading of 80 lb/ft^2, starting with an all-engine-installed thrust-to-weight ratio of 0.47, and including critical engine failure).

NASA and the Navy conducted QSRA sea trials aboard the U.S.S. Kitty Hawk (see the picture on page 3). The windspeed over the deck was 20 knots or higher, although QSRA performance would have permitted operations without wind over the deck. The trials demonstrated that powered-lift jet transports can operate aboard an aircraft carrier without the use of arresting gear and catapults (ref. 7). Depending upon

environmental conditions and mission requirements, both "free-deck" operations and operations using the arresting gear and catapults may be appropriate. NASA in-house studies revealed that the simultaneous benefits of reduced dependence on "wind over deck" and increased operating gross weights (and useful load) could be realized by modifying an existing carrier aircraft into a powered-lift configuration and operating with existing catapult and arresting gear. Example unpublished study results are given in table 2. These results compare a real aircraft to a "paper" modification of that aircraft; the resulting figures are therefore approximations only. The results, however, suggest that potential advantages may be realized by using catapults and arresting gear on aircraft that can also operate without them. The implication that requires further study is that the powered-lift approach may be the preferred approach, even for the scenario in which subsonic transport/utility aircraft operations aboard the aircraft carrier would always include use of the catapult and arresting gear (ref. 8).

The maneuverability of a powered-lift, subsonic STOL transport is demonstrated by the QSRA's turn radius of 660 ft at an airspeed of 87 knots with the critical engine failed. To illustrate, assume operation from a terminal with parallel runways. The QSRA can take off, climb to safe altitude, perform a curved climbing departure, and depart with a 180° change in heading while operating within the airspace over the center of the terminal and within the boundary between the two parallel runways. Terminal-area operations of this type would alleviate the dangers of aircraft proximity and the nuisance of aircraft noise as problems for surrounding communities.

TABLE 2.– CAPABILITY OF A-3B AIRCRAFT IN STANDARD AND POWERED-LIFT CONFIGURATIONS

Condition	Existing A-3B	Powered-lift A-3B design
Wind-over-deck, knots	20	0
Landing speed, knots (IAS)	133	89
Landing gross weight, lb	58,000	102,200
Takeoff speed, knots (IAS)	134	105
Takeoff gross weight, lb	73,000	85,700[a]

[a]Limited by catapult capacity.

To enable the QSRA to operate under adverse weather conditions, it is equipped with a modern, digital, fly-by-wire, flight-control system and electronic head-up and head-down cockpit displays (fig. 1-2) that allow the designer to overcome the inherent stability and control deficiencies that inhibit precision instrument flight (ref. 9). These deficiencies include poor longitudinal stability, large trim changes caused by thrust and flap variations, low yaw damping, and adverse yaw caused by lateral controls and rolling velocity. The controls and displays permit the pilot to achieve very precise control of the aircraft for such challenging operations as rapid decelerating transitions to landing on short fields on instruments, and to do so with modest effort and concentration on the control task itself (ref. 10). In other words, the control system and electronic displays enable the aircraft to be flown with superior flying qualities that allow the pilot to be free to devote attention to aspects of the mission environment other than those associated with control of the aircraft.

For the QSRA, this capability is achieved through pitch, roll, and yaw stabilization and command augmentation that provide precise pitch-attitude and bank-angle control and turn coordination, and, through full-authority control of the USB flaps, spoilers, and engine thrust, permit full-envelope command and stabilization of flightpath and airspeed. Head-up and head-down displays present flightpath guidance and status information in a flightpath-centered format that heightens the pilot's situation awareness for complex flight profiles and makes possible tracking performance as precise as, or more precise than, can be obtained with flight-director guidance.

Flight experiments in which the aircraft has performed rapid transitions to short-field landings along steep, curved, approach profiles, have been conducted, and these flightpath/airspeed controls and electronic displays have been assessed to have Level 1 (fully satisfactory) flying qualities by several pilots (fig. 1-3). The aircraft was considered to be exceptionally easy to control under all but the most adverse weather conditions. Even limiting crosswinds and moderate turbulence did not significantly increase the pilot's effort or degrade control precision (ref. 11). These results support the capability for tactical operations and for the utilization of damaged runways. Further flight experiments provided assessments of the contributions of this control and display technology to landing

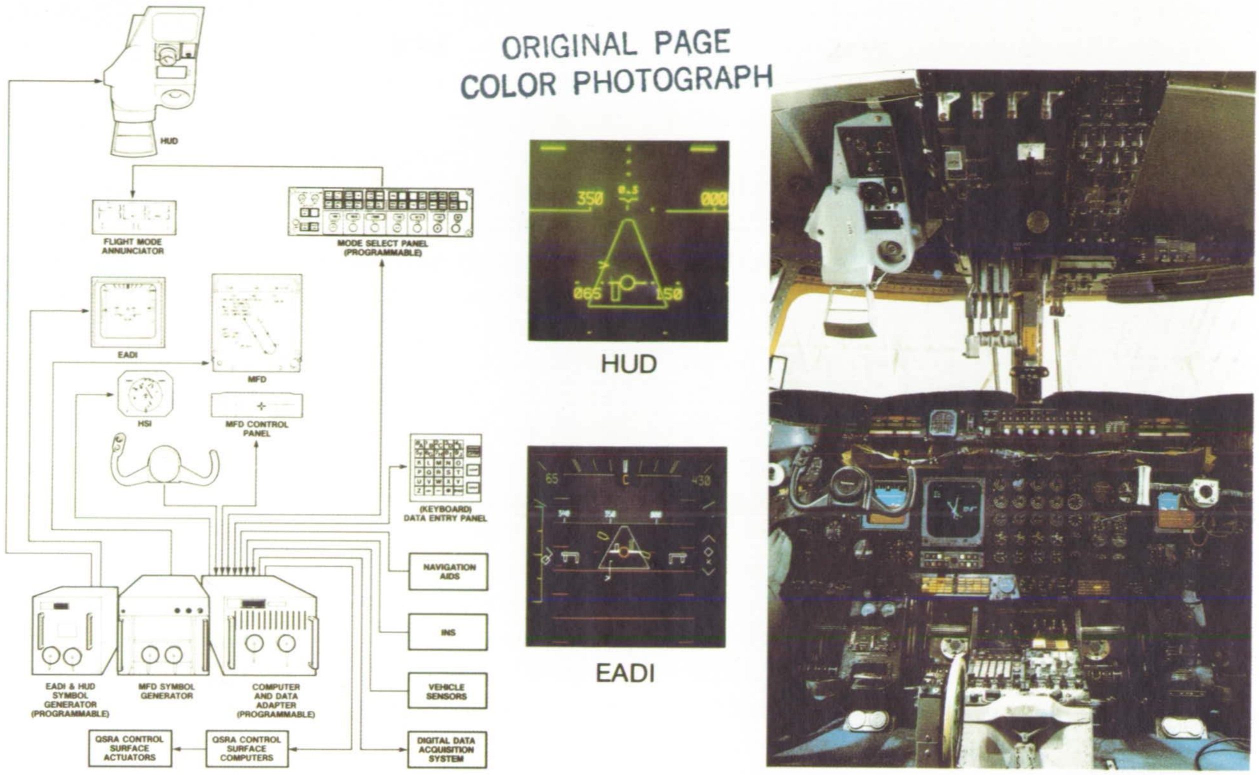


Figure 1-2*.– QSRA Research Control display and guidance system.*

precision and of the acceptability of operations to Category IIIA instrument minimums (indefinite ceiling, 700-ft visual range).

Results of this research apply to powered-lift STOL aircraft as a class, not just to the QSRA. The Lockheed High Technology Test Bed, a highly modified C-130, is being used to conduct operational evaluations of similar control modes and a head-up display as part of a demonstration of technologies for the next generation of tactical airlift aircraft.

The QSRA flight research supports the view expressed in the Introduction that powered-lift technology may be applicable to many aircraft that presently operate only from long runways and, compared to the QSRA, that have low thrust-to-weight ratios. The QSRA lands in short distances using low thrust-to-weight power settings that are equivalent to those installed on conventional aircraft. Takeoff performance was known to be critical for determining the QSRA's overall runway length requirements. Therefore, the objective of one research program was to determine takeoff performance at low thrust-to-weight ratios (ref. 12).

Reference 12 describes the flight research that measured the takeoff performance of the QSRA over a range of wing loadings and, by using partial power settings, a range of thrust-to-weight ratios. Since Ames Research Center has a C-141A, and our researchers are familiar with that aircraft, Riddle and co-workers chose this

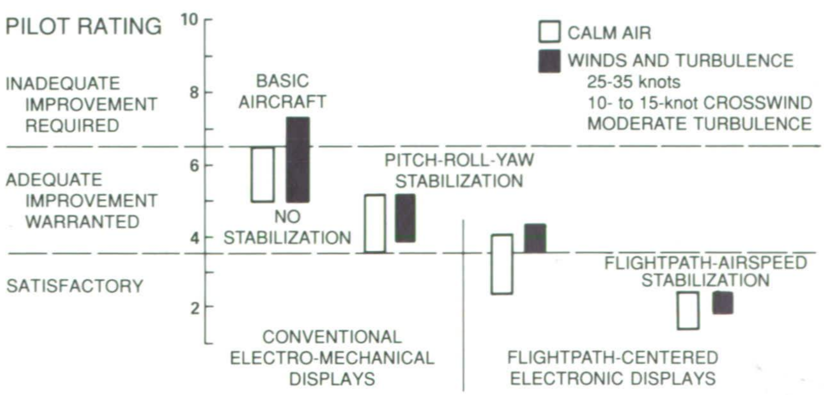


Figure 1-3*.– QSRA flying qualities evaluation.*

aircraft as a reference nonpowered-lift aircraft. The military (Air Force criteria) critical takeoff runway lengths for the QSRA and the C-141A are shown in figure 1-4. At equal wing loading and equal thrust-to-weight ratio, there is a considerable difference in the critical takeoff length for the two aircraft. With the QSRA in takeoff configuration, in-flight measurements showed that the contribution to total lift from the supercirculation component increased as thrust-to-weight ratio decreased. This finding helped explain the short takeoff performance of the QSRA at low thrust-to-weight ratios.

Using the QSRA flight results, Riddle and co-workers (ref. 12) conceptually modified the standard C-141A into a powered-lift C-141A aircraft. The design featured the same wing area and the same engines used on the standard C-141A. The design changes for the powered-lift C-141A consisted of moving the engines to over-the-wing locations and changing the flaps to include a curved Coanda flap. Takeoff performance comparisons are presented in figure 1-4. As an example, for a field length of 2500 ft (a value selected to minimize extrapolation of the QSRA flight measurements), the takeoff gross weights for the standard C-141A and the powered-lift C-141A design are about 200,000 lb and 310,000 lb, respectively.

Structural efficiency for the two aircraft was assumed to be the same (operating empty weight was 134,000 lb). Structural differences include under-the-wing versus over-the-wing engine locations, and, for those flap segments behind the engines, conventional versus Coanda flaps. The powered-lift design may or may not require thrust reversers as required by the standard design (they are not used on the QSRA). Unlike the standard design, the powered-lift design will require a few degrees of exhaust nozzle vectoring for STOL-versus-cruise configurations. Perhaps reversing and vectoring could be incorporated in the same nozzle. Cruise efficiency was also assumed to be the same. These assumptions will be addressed in future R&T activities. After additional research on USB high-speed-cruise performance and structural design studies, and additional improvements in the powered-lift low-speed configuration, the difference in takeoff gross weight at equal field length may be somewhat less (or greater) than that shown in figure 1-5, and there may be some difference in the aircrafts' empty weights. The point is that, with the same engines and for equal runway length, there will be a significant difference in load-carrying capability in favor of the powered-lift aircraft.

Reference 12 also contains the measured commercial takeoff performance of the QSRA using the guidelines of the Federal Aviation Regulations (FAR), Part 25. QSRA takeoff performance was measured for wing-loadings of 70 to 90 lb/ft^2 and thrust-to-weight ratios of 0.27 to 0.40. At equal thrust-to-weight ratios, QSRA takeoff performance was compared to, and found to be better than that of, a large number of existing commercial jet transports and business jet aircraft having a wide range of wing-loadings—including some as low as 35 lb/ft^2.

Powered-lift, subsonic STOL aircraft technology is on the threshold of expansion, because of both the military and the civil need for STOL aircraft, and the applicability of STOL technology to aircraft operating at CTOL runway lengths. For a given set of mission requirements, independent of whether STOL capability is one of them, one question to be addressed is, "Which is better, the optimally designed, powered-lift, subsonic aircraft or the optimally designed, nonpowered-lift aircraft?"

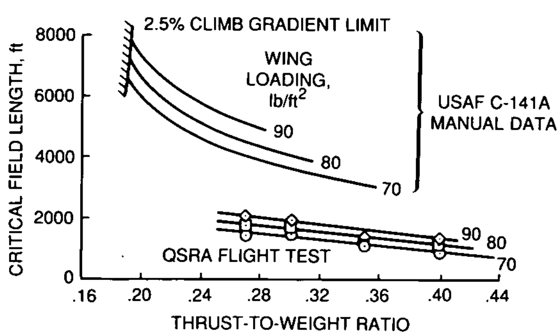


***Figure 1-4.**– Critical field length comparison for the C-141A and the QSRA.*

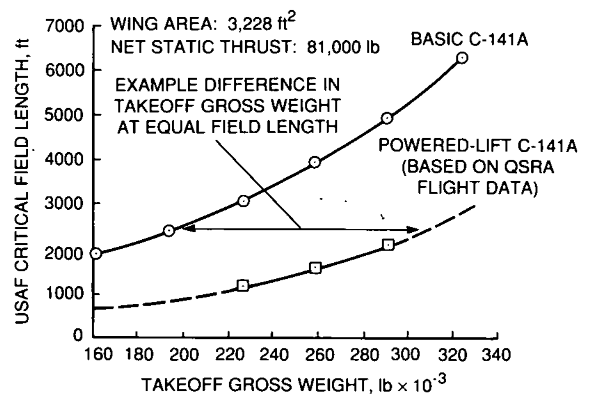


***Figure 1-5.**– Comparison of takeoff gross weights of powered-lift and nonpowered-lift aircraft at equal critical field lengths.*

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Civil tilt-rotor aircraft design by Bell Helicopter.

SUBSONIC V/STOL AIRCRAFT

The subsonic V/STOL concepts discussed here use only a fixed-wing for lift during cruise flight and have cruise airspeeds of 300 knots or more. Thus, for those concepts that use a lifting rotor, the tilt-rotor and x-wing concepts are included; helicopters and compound helicopters are not included.

A military V/STOL aircraft can perform a VTOL mission starting from a vertical-takeoff (VTO) gross weight. By operating in the short-takeoff (STO) mode, the military V/STOL aircraft can perform a STOL or STOVL mission starting from a STO gross weight that may be much greater than the VTO gross weight. Military and civil design and operating regulations differ. For STO purposes the military V/STOL aircraft has been called an "overloaded" VTOL aircraft compared to its civil counterpart.

For civil aircraft, overloading is not permitted in any context. Thus, civil V/STOL aircraft design options include

1. A V/STOL aircraft that can perform a VTOL mission although the useful load for VTO is compromised by the STO-determined structural weight. Thus, the STO gross weight can be "too much" as well as "too little"; the STO/VTO gross weight ratio is a design issue.

2. A V/STOL aircraft that can perform a VTOL mission at a VTO useful load that is not compromised, or is compromised to only a small degree, by the STO-determined structural weight. Such a design is possible if restrictions, other than STO useful load, are placed on the aircraft during STO-mode operations. An example of such restrictions would be placarding airspeeds during STO-mode operations to values lower than those for VTO-mode operations.

3. A V/STOL aircraft that operates in the STOL mode at only the "too little" VTO gross weight to realize such benefits as extended engine life through use of lower takeoff power settings and the capability to operate at maximum gross weight from high-elevation terminals on a hot day.

A pure VTOL design is required to maximize VTOL performance for both military and civil aircraft. A pure VTOL design permits the use of VTOL-only components such as minimum-weight landing gear and simple braking systems, and a wing that can be optimized for cruise flight. Typically, because of the benefits from STOL-mode operations with all engines operating and with the critical engine failed, some compromise in VTOL performance is accepted and the resulting design is a V/STOL aircraft. As technology continues to increase propulsion system thrust-to-weight ratio and decrease structural weight, a subsonic, pure VTOL design may also become a viable option.

V/STOL missions may or may not include requirements for periods of sustained hovering flight. For some V/STOL aircraft, the VTOL mode consists of dynamic maneuvers for takeoff and landing only. In either case, because of their capacity for VTOL, V/STOL aircraft have enhanced in-flight characteristics. For example, VTOL implies near independence from winds. The feasibility of operating in all weather conditions is enhanced; hence the statement, "It's easier to stop and then land than it is to land and then stop."

The STO performance of V/STOL aircraft is enhanced most significantly by takeoff-assisted, ground-based systems such as today's ski-jump ramps and catapults. This is because of the V/STOL aircraft's high thrust-to-weight ratio, thrust-vectoring capability, and power-augmented, low-speed, flight-control system. For ski-jumping, for example, some concepts use no thrust vectoring during the initial ground

roll to maximize acceleration, and rapid thrust vectoring to an optimum angle at ramp exit for a low-speed, accelerating departure.

Civil opportunities and military strategies for subsonic V/STOL aircraft are boundless. Missions can be performed that require pure VTOL, STO with mid-mission VTOL, STO with end mission vertical landing, and pure STOL.

Civil opportunities for subsonic V/STOL aircraft include new or expanded services in such areas as:

1. Ocean resource operations, with "terminals" on oil rigs, ships, and mineral exploration platforms
2. Direct city-center to city-center transportation
3. Direct corporate office to factory service
4. Transportation for underdeveloped countries
5. Transportation for inaccessible communities
6. Search and rescue
7. Emergency medical services
8. Disaster relief

Civil V/STOL aircraft are a new family of aircraft; they are not replacements for most STOL aircraft nor for most helicopters. For example, for large civil transports, STOL (or STOL application to CTOL) is feasible, whereas V/STOL is not a consideration in this context today. Sustained hovering capability combined with modest range and cruise airspeed is the domain of the helicopter. The relationship between these aircraft is viewed as complementary rather than competitive. Introduction of fixed-wing V/STOL civil aircraft will stimulate public acceptance of VTOL and STOL, with a probable result being increased sales of V/STOL and STOL aircraft and helicopters.

Military strategies for subsonic V/STOL transports are similar to those for subsonic STOL transports. For V/STOL transports and multimission aircraft, additional scenarios are possible, such as operations from small, nonaviation ships; from civil ships in times of need; and from a variety of austere, land-based, dispersed sites. Opportunities for subsonic V/STOL fighters have been proven from Harrier exercises and their record in the Falkland Islands.

There are many subsonic V/STOL aircraft concepts (summarized in table 3). The Harrier aircraft are the only V/STOL aircraft in operation. The tri-service Navy/Bell/Boeing V-22 tilt rotor is in full-scale development. Active research aircraft are the NASA/Army/Bell XV-15 tilt rotor and the research Harriers. A ground-based R&T program addresses the lift/cruise fan concept. Each concept will be discussed here.

The Harrier Aircraft

The V/STOL, vectored-thrust concept on the Harrier aircraft was conceived about 30 yr ago. Evolution of this concept into today's Harrier aircraft is without parallel in the history of powered-lift aircraft. Developments in the U.S. Marines most recent version of this aircraft, the AV-8B, include

1. Improved inlets which increase both VTO lift and cruise efficiency
2. Under-fuselage "fences," called the lift-improvement device (LID), which greatly increase VTO lift in ground effect
3. Widespread use of lightweight graphite composites, including the wing primary structure
4. A larger wing that accommodates nearly twice as much fuel as the AV-8A wing
5. Geometric rearrangement of rear nozzles, wing, and flaps to increase wing circulation lift which, when combined with the larger wing, provides about 6700 lb more STO lift on a 1000-ft takeoff run
6. Increase of the Pegasus engine takeoff thrust

As one example of performance increase, compared to the AV-8A, these improvements tripled the strike radius for a 1000-ft STO.

Over the past several years, substantial experience has been obtained with the GR MK3 and Sea Harrier by the Royal Air Force and Navy and the AV-8A by the U.S. Marines. Both land-based and shipboard operations have been carried out (fig. 2-1) by the respective services with operation from temporary runways and small pads at remote sites (ref. 13), from amphibious assault ships and small carriers, and occasionally from destroyers and frigates. During hostilities in the Falklands, the Royal Navy and Royal Air Force were able to operate consistently from their carriers Hermes and Invincible, both fitted for ski-jump launch, in low visibility and moderate seas by using special operating procedures that compensate for poor visual cues and deck motion (ref. 14). Launch from the ski jump was generally insensitive to weather conditions because of

the aircraft's docile control on exit from the ramp and greater sea clearance margins than are provided by flat-deck counterparts.

However, as a consequence of restrictive control margins in pitch and roll, large trim changes during transition, low vertical-velocity damping in hover, and adverse ground effect, routine operation in adverse weather with the earlier Harrier models was more constrained than warranted by their ability to hover and fly at low speed. For these aircraft, the only assistance provided the pilot comes from pitch-, roll-, and yaw-rate-damping stability augmentation and from the head-up display. Major improvements in controllability have been provided in the AV-8B and GR MK5 aircraft through increased

TABLE 3.– SUBSONIC V/STOL AIRCRAFT CONCEPTS

Concept	Example aircraft	Comment
Rotors		
Tilt rotor	XV-3, XV-15	V-22 scheduled for full-scale development.
Folded and/or stowed	None	Large-scale wind tunnel models.
Rotor-wing	RSRA/X-wing	Ongoing R&T.
Propeller-driven		
VATOL (tail-sitter)	XFY-1, XFV-1	No ongoing R&T.
Tilt prop	X-100, X-19	No ongoing R&T.
Tilt wing	VZ-2, X-18, CL-84, XC-142	No ongoing R&T.
Ducted prop	X-16, X-22	No ongoing R&T.
Advanced prop (propfan, unducted fan)	None	Possible future concept.
Turbine-powered		
Lift/cruise fan	XV-5	Extensive R&T, including large-scale, powered models.
Ejector augmentor	XV-4A, XFV-12	Ongoing R&T emphasizes supersonic STOVL.
Separate lift engine(s)	SC-1, DO-31, VAK-191, XV-4B	Ongoing studies.
Vectored thrust	X-14, Harriers	Harrier is only production aircraft.
VATOL (tail-sitter)	XV-13	No ongoing R&T.

roll-reaction-control authority, reduced pitch and roll trim in transition, greater lift margins, provision of lift cushion in ground proximity, and attitude stabilization through the stability-augmentation system (ref. 15). Improvements to the head-up display for indicating lateral flight limits and presenting progress through decelerating transitions to hover, which resulted from research by the Royal Aircraft Establishment (RAE), Bedford, U.K., combined with the more favorable stability and control characteristics, make these aircraft much more docile to handle in comparison to their immediate predecessors. Level-1 flying qualities can be expected for operations aboard the amphibious assault ships and small carriers.

In parallel with the development of the AV-8B and GR MK5, research in more advanced control-augmentation systems and cockpit displays has been pursued to enable V/STOL aircraft to achieve their ultimate adverse-weather operational capability at sea. Ames Research Center's Vertical Motion Simulator (VMS) (fig. 2-2) has been used in a number of investigations to explore control augmentation of the level of sophistication of decoupled attitude and translational velocity command and stabilization, including the hover-position-hold capability.

The VMS, described in reference 16, has a complex movable structure to provide six-degree-of-freedom motion that includes large vertical and longitudinal travel of ±23 and ±15 ft, respectively. This enhances fidelity of the vertical and longitudinal motions, which are particularly important for the transition and hover. The computer-generated visual scene shows a DD-963 Spruance-class destroyer with a 40- by

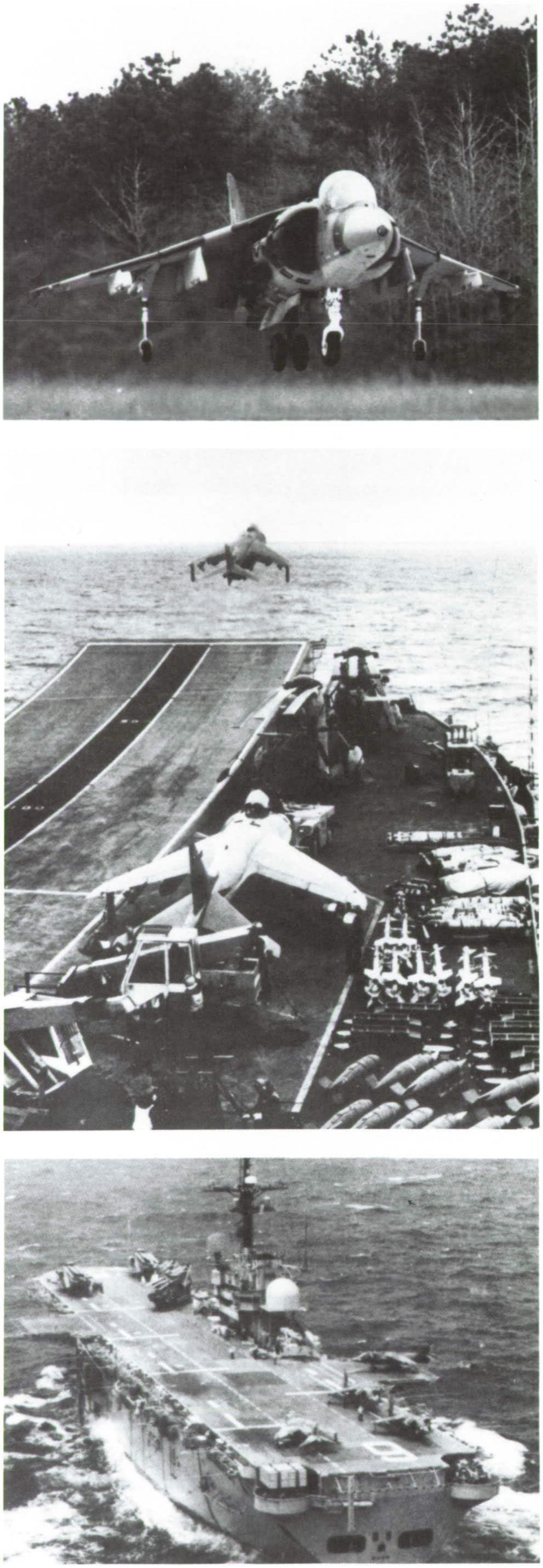


Figure 2-1.*– Harrier operations on land and at sea.*

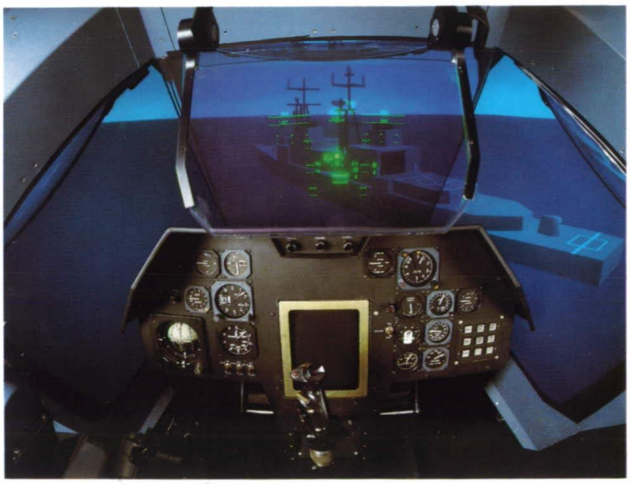


Figure 2-2.*– NASA Ames Research Center's vertical motion simulator.*

70-ft landing pad that was used in V/STOL shipboard experiments. This research has followed the path of earlier work by the Navy and NASA in conjunction with the Type-A multimission V/STOL program of the mid-1970s (ref. 17) and at Calspan on the X-22A V/STOL research aircraft (refs. 18 and 19). As shown in figure 2-3, experience with these advanced control systems suggests that Level-1 flying qualities can be obtained using velocity command controls for a fully instrument transition to hover in moderate turbulence and for low-visibility recovery to a destroyer's landing pad in heavy seas (Sea State 5-6). With attitude augmentation of the sort currently available, only Level-2 (or worse) flying qualities can be achieved for the same operational capability (refs. 20 and 21). Thus, ground-based experimental results indicate a potential for significant improvement in operational capability at sea for improved versions of the Harrier or the next generation of subsonic V/STOL aircraft. These results can be expected to apply as well to supersonic versions of these aircraft for their V/STOL operations.

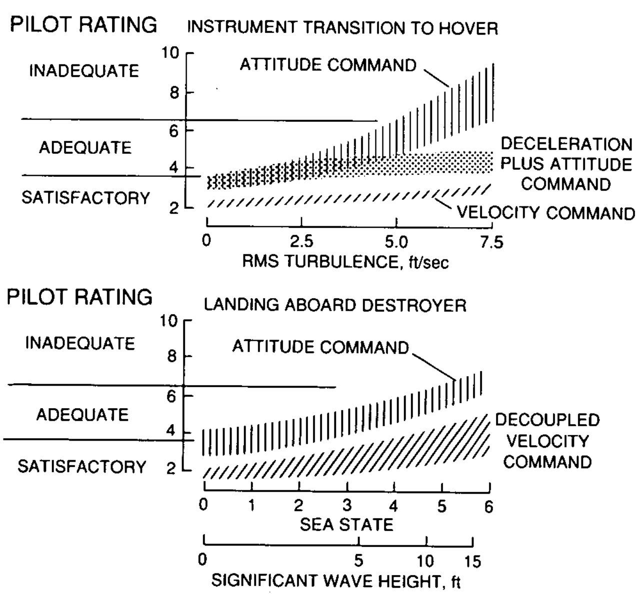


Figure 2-3.– *V/STOL flying qualities evaluation.*

Associated research in head-up displays compatible with these control modes, conducted on this simulator and in the RAE Bedford Harrier research aircraft, have shown the benefits of an uncluttered, flightpath-centered display that provides command and situation information for executing the deceleration to hover. From these experiments, the axiom has been reconfirmed that a well-designed cockpit display developed in harmony with its associated control mode is essential in achieving the full potential of control augmentation. In other words, poor display design will negate the benefits of the augmentation system.

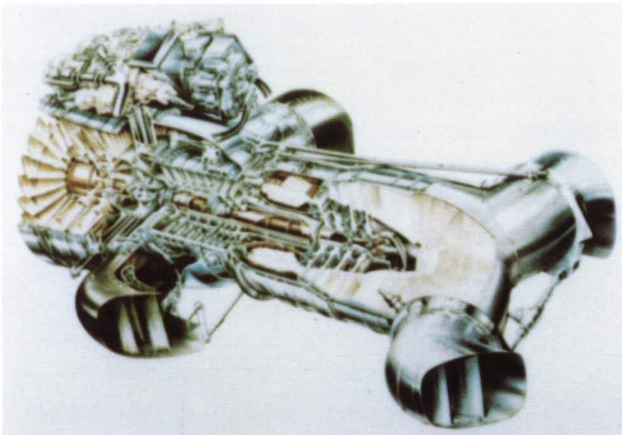
Criteria for the design of these systems and for their impact on aircraft and propulsion-system configuration are being defined in conjunction with these simulation experiments and from flight data obtained from the X-22A V/STOL research aircraft (ref. 22). The Naval Air Development Center is updating existing V/STOL flying qualities specifications (ref. 23) based on these data (ref. 24). Control power and dynamic response criteria, as well as control design sensitivities to the operating environment (winds, turbulence, ship air wake, sea state, visibility), are to be defined.

To accomplish these higher levels of control augmentation, some degree of integration of the aircraft's flight and propulsion controls is essential. The combination of aerodynamic and propulsion system force and moment generators must be defined and treated as primary flight-control elements as concerns reliability and rates and accuracy of response. Digital-control technology makes such an integrated design feasible in contrast to the limited integration possible with a hydromechanical system. Recent activities related to integrated control include simulation experiments carried out by NASA Ames and NASA Lewis researchers on the VMS with detailed dynamically accurate models of the Harrier airframe and Pegasus engine (fig. 2-4). It has been possible to assess gross thrust demands, internal engine states, and bleed-flow demands in a realistic V/STOL operational environment. Flight tests by the U.K. Ministry of Defence and the U.S. Navy of a Dowty and Smiths digital engine control system (DECS) on the Harrier have proceeded to the point that operational systems are expected to be delivered for AV-8Bs and GR MK5s. The potential for integrating these flight and propulsion controls to achieve the improvements promised by the extensive simulation results has yet to be fully explored.

The U.S. Navy and Marines have provided NASA with the YAV-8B Harrier prototype (fig. 2-5) for use in conducting a phased series of experiments to substantiate the benefits of integrated flight-propulsion controls and head-up displays and to define criteria for their design. The aircraft, now designated VSRA (V/STOL Research Aircraft), will be modified extensively to provide digital fly-by-wire controls for the pitch, roll, and yaw axes; thrust modulation and

MATHEMATICAL MODELING

AIRCRAFT - NASA AMES



PROPULSION - NASA LEWIS

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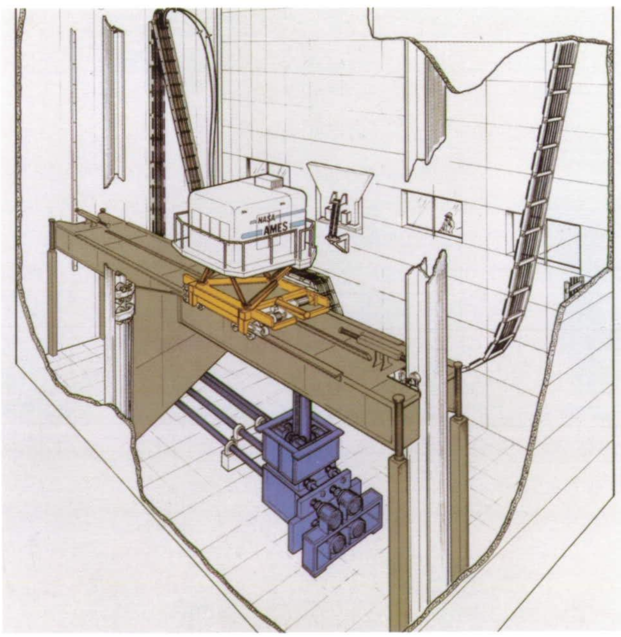


VERTICAL MOTION SIMULATOR
NASA AMES

RESEARCH OBJECTIVES
- AIRCRAFT/PROPULSION CONTROL INTEGRATION
- SAFE LOW-COST SYSTEM EVALUATIONS

Figure 2-4.– *Flight / propulsion controls research.*

thrust deflection; and a readily programmable display symbol generator that will accommodate a variety of head-up display presentations. The VSRA also has the Pegasus engine heavily instrumented to measure reaction-control bleed-flow use. The most advanced levels of velocity-command-control augmentation are being implemented through the integrated flight-propulsion control system.

This flight program will consist first of land-based operations under simulated instrument conditions and will proceed eventually to shipboard demonstrations of the operational capability that can be expected from attitude stabilization and translational velocity controls and their associated displays. At the conclusion of the planned flight programs late in 1990-91, a generic body of data will exist for V/STOL flight-control and electronic-display technology that can be applied to the development of systems for subsonic V/STOL or supersonic advanced STOVL configurations, regardless of their mission application.

Figure 2-5.– *NASA Ames V / STOL flight research aircraft (VSRA).*

The XV-15 Tilt-Rotor Research Aircraft

The external appearance and flight envelopes of the XV-15 (fig. 2-6) and a tandem helicopter are different. However, certain comparisons may be helpful. Conceptually, the propulsion and low-speed-aircraft control systems of the XV-15 tilt rotor and twin-engine tandem helicopter are similar. Each has two engines; two interconnected rotors so that upon engine failure one engine drives both rotors; no tail rotor; and, for low-speed flight, a rotor collective/cyclic system that provides control about all three axes. For a description of the XV-15, see reference 25. Unlike the tandem helicopter, the XV-15 has

highly twisted rotor blades and a wing. The twisted rotor blades increase hovering efficiency and the rotor downwash on the wing decreases hovering efficiency. The result is that for VTOL the XV-15's hovering efficiency and acoustic signature approximate those of a tandem helicopter.

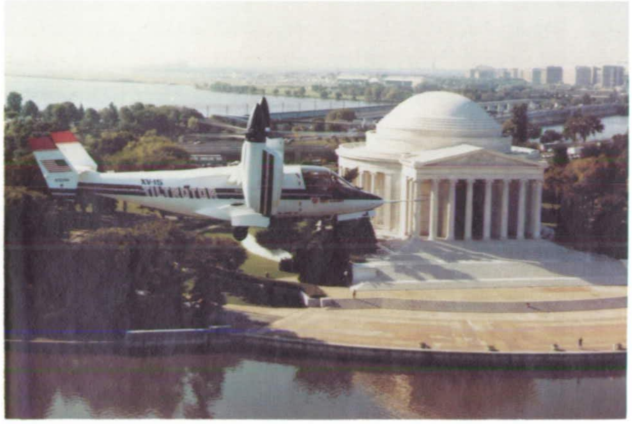


Figure 2-6.– *NASA / Army / Bell XV-15 tilt-rotor research aircraft.*

For STO, the XV-15 rotors are tilted forward a few degrees. The rotor tilt and the effects of forward speed move the downwash off the wing and the wing provides some of the lift. STO and short landing runway requirements are compatible. The XV-15's overall STOL performance is better than that of a helicopter and is competitive with or better than that of other fixed-wing V/STOL concepts. The XV-15's STO performance is most impressive when low-rotation and climb-out airspeeds (e.g., 25 knots) are used. For example, for the 15,000-lb maximum STOL gross weight and a 70° nacelle angle, the ground roll and total distance over a 50-ft obstacle are 200 ft and 400 ft, respectively, with only single-engine power. More research is needed to fully understand the XV-15's STOL performance, particularly the effect of thrust-to-weight ratio on runway length.

In the airplane mode, the XV-15 performs like a fixed-wing turboprop aircraft having a maximum cruise airspeed of 300 knots. Like the turboprop, the XV-15 flies faster than the helicopter, even when the XV-15 is cruising on one engine. Noise levels in cruise flight are low because of the use of low rotor-tip speeds.

The XV-15 is the first research aircraft with rotors that were designed to be tilt rotors. A former tilt-rotor research aircraft, the XV-3, had helicopter-designed rotors that could be tilted. Several years ago NASA initiated a research program that includes the design, fabrication, and flight evaluation of advanced technology blades (ATB), known as the XV-15/ATB program (ref. 26). One of the objectives of the program is to improve the XV-15's VTOL performance, expand the conversion envelope between helicopter and airplane modes of flight, and at least maintain cruise propulsive efficiency. Static (hovering) tests of the isolated, full-scale ATB rotor have been completed and the results verify theoretical predictions. The first flight of the XV-15/ATB was in late 1987.

The objective of another XV-15 research program was to establish the viability of three-axis sidearm controller as a primary controller for tilt-rotor aircraft. The first flight with the sidearm controller occurred in June 1985. The sidearm controller was evaluated by a broad cross-section of pilots and found to be suitable for tilt-rotor aircraft (ref. 27). Ongoing research with the XV-15 includes support for the V-22 tilt-rotor program as needed, flight evaluation of new tilt-rotor steel hubs, and more complete determination of rotor downwash characteristics, documentation of handling qualities and STOL performance.

The state of the art of tilt-rotor aircraft technology permits the design of tilt-rotor aircraft over a useful range of specifications, as evidenced by the success of the XV-15 research aircraft and the V-22 program. The V-22 will be a "first-generation" aircraft, and researchers are continuing to advance technology for improved second-generation aircraft. An example of a characteristic being investigated that will yield significant improvement for future tilt-rotor aircraft is the reduction of wing download during hovering flight caused by rotor downwash (ref. 28). Various mechanical and pneumatic schemes are being studied that may reduce the rotor-induced download on tilt-rotor configurations to values approaching those experienced by helicopters.

A general perception is that a civil V/STOL aircraft must be a derivative of a military V/STOL aircraft because of the high cost of development for a new type of aircraft. The military V-22 tilt-rotor V/STOL aircraft is in development. The tilt-rotor concept has civil potential because of its VTOL- and STOL-mode capabilities, fuel efficiency, and low noise and vibration levels. Hence, the first civil V/STOL aircraft may soon be forthcoming (ref. 29). The success of the first civil V/STOL aircraft will depend on many factors, one of which will be the V/STOL certification requirements. The requirements must yield a

safe aircraft with sufficient, but also not excessive, operating margins. A joint FAA/NASA effort is in progress to establish V/STOL certification criteria.

An augmented civil tilt-rotor technology program is being advocated. Tilt-rotor application studies have been completed. Proposed research would augment ongoing, moving-base, simulation studies and initiate the use of the XV-15 to establish civil V/STOL certification criteria. A ground-based activity would address the feasibility of tilt-rotor aircraft with and without one-engine-out VTOL capability. One approach to a civil tilt-rotor design might be one in which one-engine-out VTOL and a 350- to 400-knot cruise airspeed are complementary requirements. Technology for a high-speed tilt rotor may be an appropriate subject because of the benefit from higher cruise airspeed and the possibility of it being a complementary design requirement.

The RSRA/X-Wing Research Aircraft

The RSRA/X-wing research aircraft addresses the subsonic V/STOL rotor/wing concept. The rotor/wing, folded-rotor, and stowed-rotor concepts use a helicopter-like rotor for low-speed flight and a propulsive device other than the rotor for high-speed flight. These concepts offer a solution for achieving, in one aircraft, helicopter-like VTOL performance, STOL-mode capabilities, and high cruise airspeeds (~500 knots). Some of the concepts may offer the potential to cruise at transonic airspeeds. Research and technology efforts for each of the following concepts has included large-scale wind tunnel investigations.

1. Rotor/Wing: For cruise flight the rotor is stopped and indexed, and the rotor blades become either the only fixed-wing or one of the fixed-wings on the aircraft. The most recent example is the X-wing.

2. Folded Rotor: For cruise flight the rotor is stopped, folded, trailed in a streamwise direction, and blended into the configuration as much as possible, but not stowed inside the airframe. Studies are continuing on such configurational variants of the folded-rotor concept as the folded tilt rotor and the trail rotor (ref. 30).

3. Stowed Rotor: For cruise flight the rotor is stopped, folded (or possible even left unfolded), and stowed inside the fuselage or wing, or both. The concept has not been studied recently.

The RSRA/X-wing (fig. 2-7) has a four-bladed rotor that is mechanically driven and pneumodynamically controlled (ref. 31). Turboshaft engines drive the rotor and an air compressor, and separate engines provide propulsive thrust. Compressor air is ducted to the rotor blades and to both leading- and trailing-edge slots of symmetrical circulation-control airfoils. With the rotor rotating, the pneumodynamic system provides lift, and pitch and roll control; the tail rotor/rudder provide yaw control. With the rotor stopped, the pneumodynamic system provides lift and, if desired, pitch-control augmentation; the rotor mechanical collective (i.e., differential left-right wing incidence) provides roll control; and the elevator and rudder provide pitch and yaw control. An air supply to the circulation-control airfoils is required at all times. Figure 2-7 illustrates the circulation-control modes that correspond to various flight modes. For research and safety purposes, the RSRA will be in the compound helicopter configuration, which includes a "fixed" wing having ailerons, flaps, and in-flight variable incidence. The variable-incidence fixed wing will be used to incrementally transfer lift to the X-wing. The compound configuration will enable flight research with and without the X-wing's pneumodynamic system.

The RSRA/X-wing configuration includes a quadruple-redundant, digital-based control system. Control algorithms include hub moment

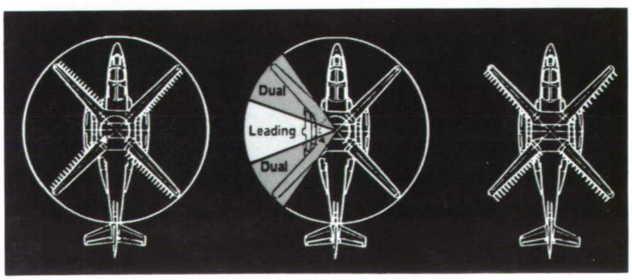


Figure 2-7.– NASA/DARPA/Sikorsky Rotor Systems Research Aircraft (RSRA)/X-wing.

feedback to control the stiff rotor and its associated gyroscopic moments, and higher harmonic control to reduce the vibrations caused by the stiffness and the circulation control.

The objectives of the RSRA/X-wing activity are to design and fabricate an X-wing rotor and control system and to evaluate this technology on the RSRA during specific modes of flight. The RSRA/X-wing flight regime corresponds to an airspeed range between ~125-250 knots. The helicopter-mode, low-speed regime and the airplane-mode, high-speed regime are not part of the RSRA/X-wing activity. The first flight of the RSRA/X-wing research aircraft was in late 1987. For the first flight the aircraft was in a baseline research configuration, which did not include installation of the X-wing rotor. Soon after the first flight, funding cuts mandated a need to restructure the program; this restructuring is in progress.

Today's rotor/wing and folded-rotor designs are complex; R&T can reduce complexity. Originally, both the tilt-rotor and the lift/cruise fan designs were "too complex." The separate propulsion systems found on past rotor/wing and folded-tilt-rotor designs will be replaced with convertible engines that deliver shaft power, thrust, and combinations of the two. A NASA/DARPA/GE activity that featured modification of a TF-34 engine has demonstrated the feasibility of convertible engines. A proposed X-wing technology demonstrator (following the RSRA/X-wing program) features convertible engines. Means have also been proposed to eliminate the X-wing's mechanical collective control. Some complexity is acceptable if it creates new opportunities. An exciting goal for powered-lift technology is an aircraft that has helicopter-like low-speed performance and also a high subsonic (or even higher?) cruise airspeed.

The Subsonic V/STOL Lift/Cruise Fan Concept

The V/STOL lift/cruise fan concept is generally investigated with respect to a transport/multimission aircraft designed for VTOL, with a modest hovering mission requirement, a high subsonic cruise Mach number, and capability to cruise at high altitudes. Compared to past lift/cruise fan concepts, and to competing subsonic V/STOL transport concepts, today's lift/cruise fan concepts feature simplicity.

Historically, initial configurations featured the fan-in-wing concept, and one configuration reached flight status—the XV-5. The fans in the wing were separate lifting fans used only for VTOL and low-speed flight. The terminology "lift fan concept" was commonly used. The fan-in-wing lift fan was superseded by the fan-in-fuselage pod lift fan and the fan-in-wing pod lift fan concepts. All these concepts featured separate lift fans. More recently, many designs feature high bypass turbofans that provide both the lift for VTOL and the thrust for cruise flight. There are no separate lift fans; hence, the concept is known as the lift/cruise fan.

To provide lift and some thrust for near wind-independence for VTOL, and thrust for cruise flight, the lift/cruise fan propulsive force must be vectored by somewhat more than 90°. There are two basic design approaches for achieving the required vectoring. In one approach, the entire turbofan is rotated as a unit. One lift/cruise fan variant of this type is the tilt nacelle. In the other approach the fan and core gas generator always remain in the horizontal position and the fan efflux and the hot core exhaust are deflected. The names for these latter concepts are derived from the design approach used to deflect the exhaust gases.

Lift/cruise-fan concepts are also named with respect to the number of vertical jet exhaust columns or "posts" emitted during VTOL. The number of posts is not necessarily the same as the number of engines; i.e., the fan and hot core gases may be deflected independently. Past R&T investigations established an extensive data base for many-posters, four-posters, and three-posters. A goal for more recent R&T activities has been to establish a data base for the two-posters.

One recent NASA/Navy activity addresses the lift/cruise fan, twin-nacelle two-poster. There are several configurational variants of the twin nacelle. One design by Grumman Aerospace Corporation is represented by the large-scale powered model shown in figure 2-8.

Except for the part of the system that tilts the nacelles, all VTOL-related components are located in the twin nacelles and the structure on which the twin nacelles are mounted. The fuselage, empennage, and wing volumes are thus available to the "normal" degree. The VTOL-related components include the turbofans, a fan mechanical-interconnect system, and the low-speed control-force generators for all three axes; the turbofans are also used for cruise flight. The VTOL-related systems are also useful for such

non-VTOL flight modes as continued flight and roll-on landing with one engine failed.

For VTOL, heave-, roll-, pitch-, and yaw-control forces are generated by turbofan thrust modulation, variable-incidence fan-inlet guide vanes, and vanes in the turbofan exhaust streams. The pitch and yaw vanes are located in the fan efflux, and are in close proximity to, but not in, the hot core exhaust (see fig. 2-8). Experimental results verified that the pitch and yaw vanes generate satisfactory control forces and moments. For cruise flight, conventional aircraft controls are used.

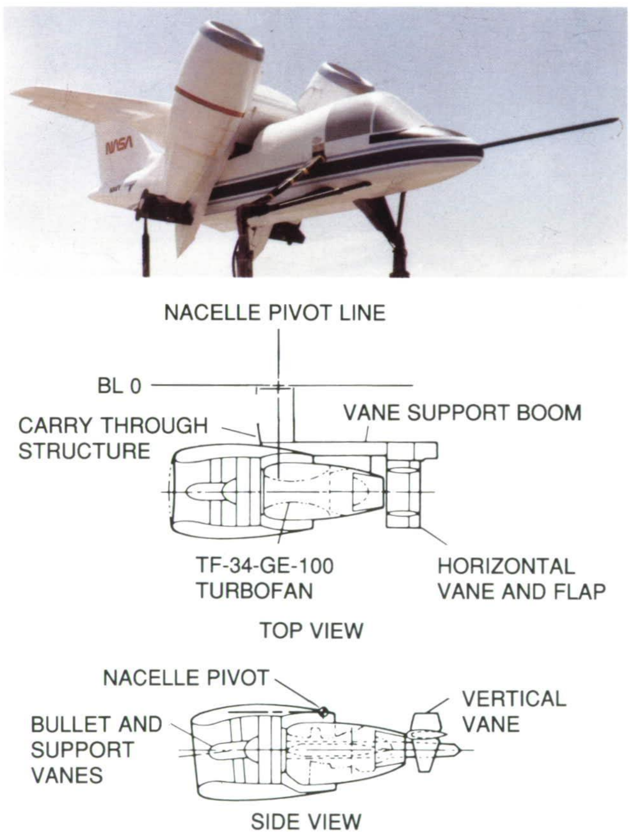


Figure 2-8.– *NASA/Navy Grumman large-scale, powered, tilt-nacelle model.*

One of the classical concerns for lift/cruise-fan aircraft is ground effects. Ground proximity can cause pronounced effects, including changes in vertical force, upsetting control moments, and engine reingestion of hot gases. Ground effects for the tilt nacelle were found to be relatively benign (refs. 32 and 33). For example, consider the vertical forces: Ground proximity can produce vertical-force changes in either direction that are unacceptable. During landing, a force change that results in a rapid acceleration toward the ground or a change that balloons the aircraft back into the air is undesirable. For the large-scale, tilt-nacelle model, the effect of ground proximity on the vertical force was "about right," i.e., within the range from acceptably positive to acceptably negative.

A lift/cruise-fan, twin-nacelle, two-poster design by McDonnell Aircraft Company (McAIR) is the vectored-thrust concept shown in figure 2-9. The design features two shoulder-mounted, high-bypass turbofan engines that remain fixed in the cruise position. For VTOL, "vented D" engine nozzles are used to vector the propulsive force 90°. Venting of the D-shaped nozzled is accomplished by removing the inside wall of the elbow turn of a conventional deflector nozzle. In a NASA/McAIR program using a TF-34 engine, it was verified that the vectoring performance of the vented D-shaped nozzle was higher than that of several nonvented nozzle designs (ref. 34).

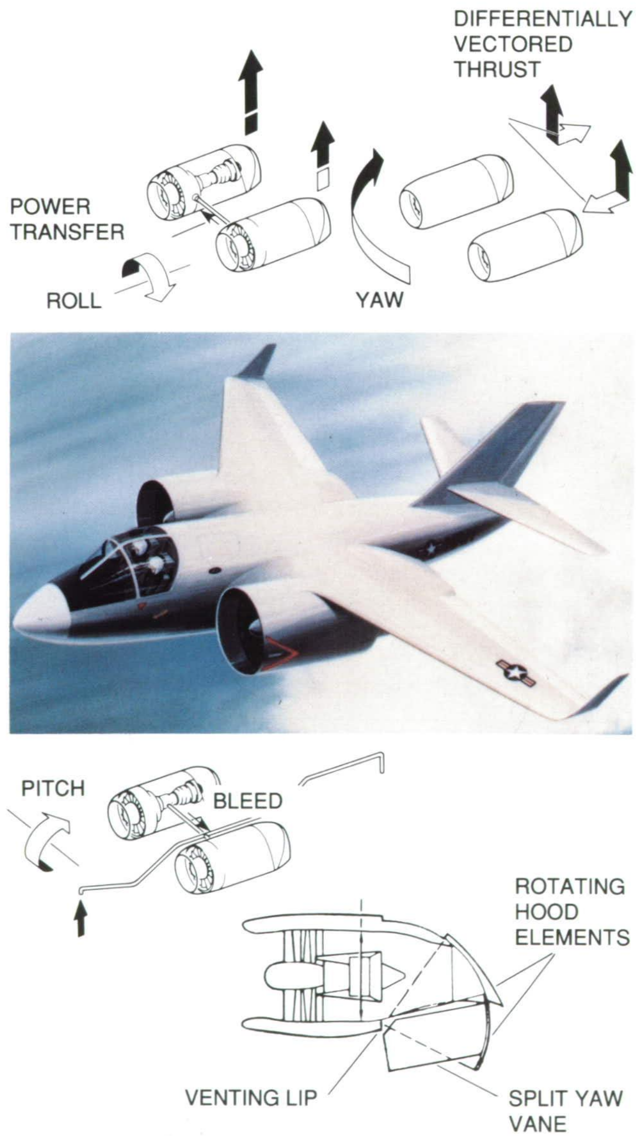


Figure 2-9.– *Navy/McAIR twin-engine, vectored-thrust lift/cruise fan aircraft concept.*

Control in low-speed flight is provided by an engine-bleed, reaction-control system in pitch, differential thrust (i.e., lift) modulation in roll, and differential thrust vectoring in yaw (see figure 2-9). Power transfer between mechanically interconnected fans permits a wide range of thrust modulation for roll control, including engine-out balance capability.

Lift/cruise-fan R&T investigations have been extensive. Research has included all types of ground-based R&T: aircraft conceptual, preliminary, and selected-detail design studies; prediction, free-flight, and small-scale wind tunnel investigations; large-scale static facility and wind tunnel investigations; and many simulations, including several piloted, moving-base simulations. Under the Navy's Medium-Speed V/STOL Technology Program, Grumman and McAIR refined candidate designs. One research activity being planned features the cross-shafting of two TF-34 engines. The large-scale, powered, tilt-nacelle model will be one of the first research models installed in Ames Research Center's new 80- by 120-Foot Wind Tunnel. Lift/cruise fan technology is a mature technology. It is now at the point at which the next logical step is the creation of a research aircraft or, as it is sometimes called, a technology demonstrator.

In summary, subsonic V/STOL aircraft technology is on the threshold of expansion. Military interests are evident from the production of the Harrier series and the development of the V-22 tilt rotor. Most V/STOL R&T activity has been applicable to military aircraft or has been generic in the sense of being applicable to both military and civil aircraft. An R&T thrust for civil-unique subsonic V/STOL technology is needed, with near-term emphasis on the civil tilt-rotor aircraft.

ORIGINAL PAGE
COLOR PHOTOGRAPH

Air Force/McAIR F-15 STOL aircraft.

SUPERSONIC STOL AIRCRAFT

Supersonic STOL aircraft technology has been investigated in the context of its application to fighter aircraft. One military strategy features operations from damaged runways, as illustrated in figure 3-1. We are not aware of interest in supersonic STOL transport/bomber aircraft.

Supersonic fighters that have enhanced runway-length performance also have enhanced in-flight capability. Depending on mission requirements, the in-flight enhancements (e.g., high angle-of-attack capability and supermaneuverability) can be the design drivers and STOL capability then becomes the design fallout benefit.

R&T has addressed supersonic, STOL, two-engine, fighter concepts that feature integration of the wing, engines, and vectorable exhaust nozzles. For these advanced two-engine concepts, lift for STOL is provided by the wing and by the vectored propulsive force. One such concept is known as the vectored engine-over (VEO) flap, which is similar in principle to the USB concept discussed for subsonic STOL aircraft. One R&T activity was a wind tunnel investigation of a large-scale model of a highly maneuverable supersonic fighter (ref. 35). The model combined VEO flaps and spanwise blowing to augment lift over a wide angle-of-attack range. The model was equipped with close-coupled canards and was powered by two turbojets (fig. 3-2). A significant feature of the basic flow field was a leading-edge vortex that created an inboard boundary for a separated flow region. The USB and spanwise blowing enhanced lift and delayed stall. The hot spanwise blowing jet mixed rapidly with the wing flowfield and generated only a moderate temperature rise on the wing surface.

Exploratory, small-scale, wind tunnel investigations have addressed supersonic STOL concepts that feature the forward-swept wing. Results indicate compatibility of the forward-swept wing to powered-lift approaches such as blown flaps and wing spanwise blowing. A forward-swept wing design "clears out" the mid-fuselage area where powered-lift propulsion systems tend to be located. Assessments of the potential of the forward-swept wing should include its applicability to both CTOL and powered-lift aircraft.

Recently, supersonic STOL technology has addressed configurations that are like those found on existing one- and two-engine fighter aircraft. The engine(s) are located in, or blended with, the fuselage. The engine exhaust nozzle(s) are located in or near the aft fuselage, a location that is relatively remote from the wing. Vectorable

Figure 3-1. *– Air Force/McAir F-15 STOL aircraft approaching a damaged runway.*

Figure 3-2. *– Large-scale model of a highly maneuverable supersonic STOL fighter.*

nozzles or vanes in the engine exhaust flow are used to vector the propulsive force to augment pitch control, or both pitch and yaw control, or, for two-engine fighters, possibly control about all three axes. Research by NASA Langley Research Center and the Air Force has shown that the power-augmented controls permit a variety of in-flight enhancements. For STOL the propulsive force is not deflected to provide powered lift. The power-augmented pitch control is used to control wing angle of attack at lower than normal airspeeds (e.g., to reduce nose-wheel liftoff airspeed and thus enable the wing to provide all of the lift required for STO). One of the advantages of this technology is its potential applicability to existing fighters.

The Air Force has initiated a technology demonstration program for an aircraft of this class (ref. 36). Under the STOL and Maneuver Technology Program, McDonnell-Douglas has been awarded a contract to modify an F-15 airframe to incorporate several features that provide a capability for short-runway operation in adverse weather, and enhanced maneuverability. Powered-lift features are not included in this design; instead, the aircraft will utilize a close-coupled canard, two-dimensional thrust vectoring and reversing nozzles, flaperons, ailerons, and lifting stabilators to increase lift and augment control at low speed. A full-authority digital control will integrate the aerodynamic surfaces and propulsion system to achieve precise flightpath control for the approach and landing, rapid deceleration immediately upon touchdown, and steering during rollout on slippery runways in crosswinds. Enhanced maneuverability will also result from the combination of aero/propulsion controls, appropriately applied for rapid turns, fuselage pointing, acceleration, or deceleration. Pratt and Whitney Aircraft Division is responsible for developing the exhaust nozzle for thrust vectoring and reversing; General Electric, for digital flight/propulsion control hardware and software; and Honeywell, for integrated control laws. First flight was in 1988 with the aircraft in a configuration that did not include the two-dimensional thrust-vectoring nozzle. Flights with this nozzle installed are scheduled for 1989.

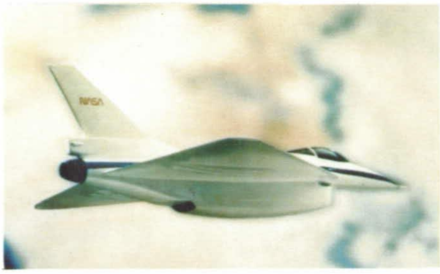
Powered-lift STOL technology may also be applicable to supersonic civil aircraft, particularly in the context of its applicability at CTOL runway lengths. Powered-lift may be useful during subsonic flight modes such as takeoff, climb, approach, and landing. An efficient supersonic wing design is required for supersonic cruise. An improved wing design may be possible if it is less compromised by takeoff and landing considerations.

One civil opportunity for supersonic STOL aircraft technology may be its applicability to business jet aircraft. Technology for supersonic STOL fighters and for subsonic STOL civil aircraft should be reviewed with respect to its applicability to supersonic business jets. Depending upon the design, advantages for the powered-lift, supersonic business jet might include increased payload/range and reduced noise levels from steeper-gradient flight. Some STOL aircraft have a near-level fuselage attitude during landing approach. Perhaps a powered-lift, supersonic business jet would not need such added features as a hinged forward fuselage to enhance visibility on landing approach. Studies need to be conducted to help determine which is the best supersonic business jet design: (1) a pure CTOL aircraft; (2) an aircraft with a modest amount of STOL technology that operates only at the runway length of the CTOL aircraft; or (3) a STOL aircraft that operates always, or sometimes, from substantially shorter runways than does the CTOL aircraft.

It is too early to conclude that powered-lift, supersonic, STOL aircraft technology is on the threshold of expansion. Advanced supersonic STOL fighter designs will feature a high thrust-to-weight ratio as required for supersonic flight, and perhaps power-augmented aircraft control

systems as required for high-angle-of-attack capability. These features are basic elements of STOVL designs, discussed in the next section. Although they are designed for vertical landing, many STOVL aircraft may operate in the STOL mode to minimize constraints associated with pure vertical landings, such as impingement of high-temperature and high-velocity exhaust gases on the landing surface. Nevertheless, technical, cost, and operational tradeoffs could be such that for supersonic fighter aircraft designing to a STOVL capability may be favored over designing to a powered-lift STOL capability. For nonpowered-lift STOL fighter aircraft the application of powered-lift-related technology, such as thrust vectoring for control, is under serious consideration. For civil supersonic aircraft the applicability of powered-lift technology needs to be clarified, and the economic viability of the optimal design must be determined.

VECTORED THRUST



EJECTOR AUGMENTOR

TANDEM FAN

REMOTE AUGMENTING
LIFT SYSTEM (RALS)

Conceptual designs of supersonic STOVL aircraft.

SUPERSONIC STOVL AIRCRAFT

Supersonic STOVL aircraft technology is being investigated in the context of its application to fighter aircraft. We are not aware of interest in supersonic STOVL military transports. Technology for supersonic civil aircraft capable of vertical flight may not be of interest for some time because of the costs associated with supersonic STOVL civil aircraft, or more correctly, the costs associated with supersonic V/STOL civil aircraft. (Operational scenarios for subsonic and supersonic civil aircraft capable of vertical flight typically require VTOL or V/STOL, not STOVL, capability.)

Based on experience with the subsonic Harrier aircraft, perceived modes of operation for a supersonic fighter, and performance and cost tradeoffs at today's technology level, the supersonic fighter aircraft capable of vertical flight is typically designed to a STOVL capability. A STOVL aircraft usually operates from short runways, although it does have an important vertical flight capability. Compared to a V/STOL aircraft, a STOVL aircraft has a modest VTO capability. The VTO gross weight can be no more (or very little more) than the vertical landing gross weight. When attempts are made to design a supersonic STOVL aircraft, it may be found that an in-flight requirement rather than the vertical landing requirement dictates the required aircraft thrust-to-weight ratio. If so, the design should be described as a V/STOL design, or the in-flight requirement should be relaxed to yield a STOVL design.

Compared to a STOL aircraft, the STOVL aircraft features a higher level of STO performance as a result of the high aircraft thrust-to-weight ratio and the high level of aircraft controllability associated with vertical landing. The STOVL aircraft can take off from long runways, short runways, or very short (e.g., 300 ft) runways, as required. The STOVL aircraft can operate in what some have called the super-STOL mode. Researchers consider STOVL and V/STOL to be synonymous because the technological needs are the same.

Military strategies for supersonic STOVL fighter aircraft are based on operations from austere dispersed sites, solution for total runway denial, enhanced operations from aircraft carriers, operations from small nonaviation ships, and enhanced in-flight capabilities of the aircraft. The enhanced in-flight capabilities of STOVL aircraft include improved acceleration, deceleration, controllability at high angle-of-attack, and supermaneuverability. The enhanced in-flight capabilities are due to the large range of thrust vectoring available and the high level of aircraft controllability. The enhanced in-flight capabilities of STOVL aircraft may be significant to the degree that STOVL is a competitive design approach,

even for that scenario in which STOVL terminal-area operations are of secondary or tertiary importance.

A supersonic STOVL fighter aircraft has not yet reached production. Two research aircraft (preproduction) capable of vertical flight have attained supersonic flight. The lift engine plus twin-tilt-nacelle VJ-101, after a vertical takeoff, barely exceeded Mach 1. The lift engine plus lift/cruise engine Mirage III-V, after a conventional takeoff, exceeded Mach 2.

Several existing supersonic STOVL aircraft concepts are shown in table 4. All these concepts could be applied to two-engine aircraft, but only some are applicable to one-engine aircraft. The concepts applicable to two-engine aircraft are named either for an airframe configuration (e.g., tilt nacelle or tilt wing) or for the type of advanced propulsion system used (e.g., ejector augmentor or tandem fan). Nearly all of the concepts applicable to one-engine aircraft are named for the type of advanced propulsion system used. STOVL concepts named for an airframe configuration could use the same propulsion system used in CTOL or STOL supersonic fighter aircraft. STOVL concepts named for a propulsion system require significant modifications to CTOL-type propulsion systems and/or the addition of propulsion system components unique to STOVL (e.g., remote, augmented-lift system). The propulsion system holds the key to the success of a supersonic STOVL fighter aircraft. That is particularly true for those concepts that require an advanced STOVL propulsion system. Technological needs for the propulsion system include high thrust-to-weight ratio, low volumetric installation requirements, fore and aft vertical-thrust splits that yield aircraft balance in vertical flight, jet-plume temperatures, velocities, flow patterns, acoustic signatures that yield acceptable ground effects, and innovative propulsion system/airframe/controls integration.

Considerable effort has been applied to broad-based generic R&T, such as prediction and experimental verification of jet-plume characteristics and ground effects, and to R&T that focused on technology for two-engine, supersonic STOVL fighter aircraft. Investigations have

TABLE 4.– SUPERSONIC STOVL AIRCRAFT CONCEPTS

Concept	Example aircraft	Comment
Vectored thrust	None	Small-scale wind tunnel models; PCB tests in UK.
Ejector augmentor	None	Small-scale wind tunnel models, large-scale generic model.
Tandem fan	None	Design studies.
Remote augmenting lift system (RALS)	None	Design studies.
Lift engine(s) and lift/cruise engine	Mirage III-V	Several large-scale wind tunnel models.
Tilt nacelle	VJ-101	Design studies.
Tilt wing	None	Design studies.
VATOL (tail-sitter)	None	Large-scale wind tunnel model.

included aircraft conceptual design studies for those concepts shown in figure 4-1, and small- and large-scale wind tunnel investigations for several of these concepts. Reference 37 contains a summary discussion and provides dozens of references on the subject.

To expand the existing data base, recent R&T investigations have focused on the one-engine, supersonic, STOVL fighter aircraft, primarily for those concepts known as vectored thrust, ejector augmentor, tandem fan, and remote, augmented-lift systems. For each concept there are several propulsion system configurational variants, and for each propulsion system variant there are many possible airframe configurations. A brief description of one propulsion scheme for each concept follows (see ref. 1).

Vectored Thrust

Exhaust flow from a separate-flow turbofan is directed through four nozzles which are continuously vectorable. This arrangement permits vectoring in forward flight. Engine fan and core streams are deflected separately. The fan flow through the two forward nozzles is augmented by fan-stream burning for vertical flight and supersonic cruise. The basic engine is conventional; i.e., there is no internal flow-switching.

Ejector Augmentor

The lifting thrust of the engine is augmented by an air-to-air ejector. With an unmixed engine, fan air is directed through the primary ejector nozzles, which may be vectorable to aid the conversion process. The ejector primary jets entrain secondary mass airflow through the ejector, which augments the lifting thrust of the fan air. In cruise flight, fan air and core exhaust are directed through separate nozzles, each of which may feature an afterburner, as required.

Tandem Fan

A variable-cycle engine provides a low-bypass, mixed-flow, reheated turbofan for cruise flight, and a high-bypass, unmixed configuration with vectored nozzles for VTOL. The fan is in two sections separated axially on a common elongated shaft to accommodate a flow diverter valve and an auxiliary inlet. The nozzles are vectorable, allowing transition independent of engine mode. In a "hybrid" version of the tandem fan, the high-bypass, "parallel-flow" mode can be used for long-range subsonic cruise/loiter.

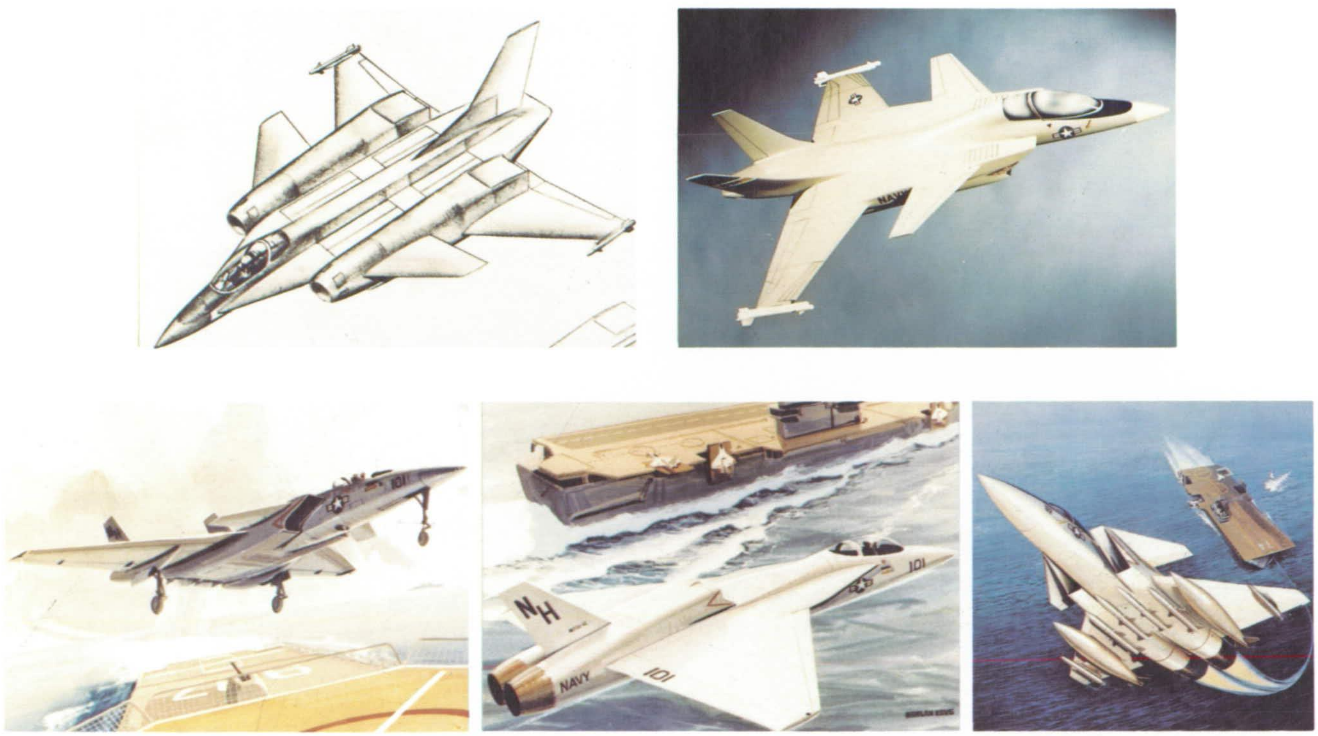


__Figure 4-1.__– Conceptual designs of two-engine supersonic STOVL aircraft.

Remote, Augmented-Lift System

For vertical flight the fan air of a turbofan is diverted to a position forward of the fan (hence, remote). The fan air is augmented and directed downward through a vectorable nozzle. For cruise the fan-air-diverter valve is closed and the fan flow is mixed with the core exhaust. The arrangement allows design flexibility in the fore-aft fuselage location of the turbofan.

One NASA/Navy/industry activity included aircraft design studies and small-scale models for high-speed wind tunnel investigations. An 11% flow-through model fabricated by General Dynamics was based on the ejector augmenter concept (see figure on page 25). The model was tested in various cruise flight configurations over a wide range of Mach numbers.

The studies addressed several high-speed aerodynamic uncertainties. One concern was the large vertical surface of the forward fuselage which forms the inboard ejector diffuser surface (because of its potentially destabilizing effect on lateral/directional stability). Another concern was the limitation to optimal wing design imposed by the ejector augmentor in the wing root. Also of concern was afterbody drag because of the unique integration of the two-dimensional core nozzle with the under side of the fuselage (see ref. 37).

Another element of the NASA/Navy activity included a 9% flow-through and jet-effects model fabricated by McDonnell Douglas based on the vectored-thrust concept. The flow-through model, shown in figure 4-2, was investigated in various cruise flight configurations. On the jet effects wind tunnel model, both cruise and fan-stream burning nozzle settings were evaluated using high-pressure air. Aerodynamic uncertainties included the canard contribution to high-angle-of-attack lateral/directional instability, supersonic minimum drag, propulsive flow effects on transonic drag, and the jet-plume interference effect on downstream aircraft surfaces.

***Figure 4-2.**– NASA/Navy/McAIR small-scale model of a vectored-thrust supersonic STOVL aircraft.*

Wind tunnel results are used to validate computer programs. PAN AIR is a computer program for predicting subsonic or supersonic linear potential flow about arbitrary configurations. As an example, PAN AIR was applied to the complex configuration shown in figure 4-2. Complexities included a close-coupled canard/wing, large inlets, and four exhaust nozzles mounted directly under the wing and against the fuselage. Examples of the PAN AIR paneling of the configuration are shown in figure 4-3. As concluded in reference 38, results demonstrated the ability of PAN AIR to effectively predict the aerodynamics of a complex aircraft geometry in subsonic or supersonic flow under cruise conditions.

Also completed were aircraft design studies for the one-engine, tandem-fan and remote augmented-lift system (ref. 39). Plans include small-scale, high-speed wind tunnel investigations of these concepts.

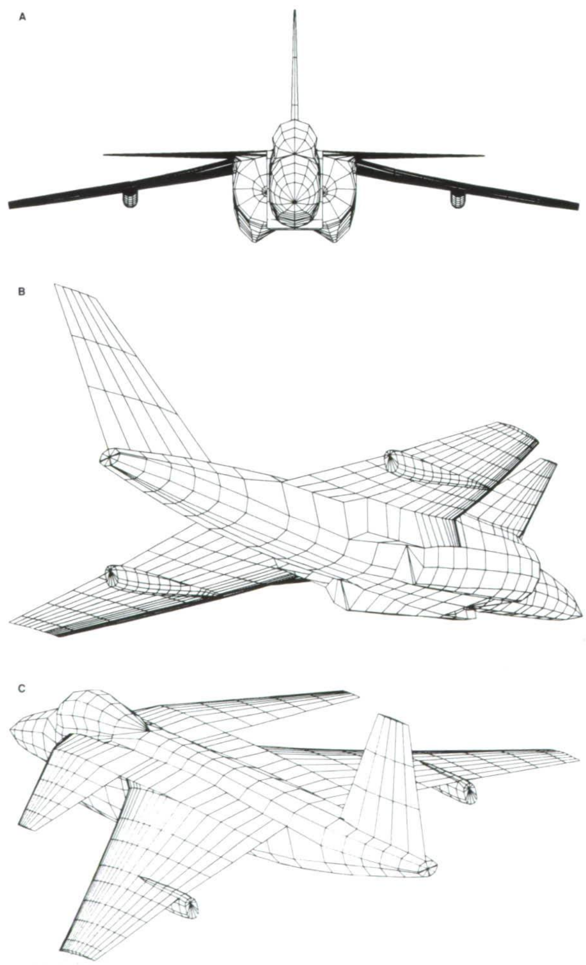


***Figure 4-3.**– PAN AIR paneling of the model of figure 21.*

One of the activities on supersonic STOVL one-engine concepts is a joint NASA/Navy/ Canadian program on ejector-augmentor technology. Program objectives include developing a fundamental understanding of the fluid dynamics of the ejector and its integration into the complete propulsion system. One concern is how to package the ejector system, which typically has high volume requirements, within the lines of a practical aircraft configuration. The program

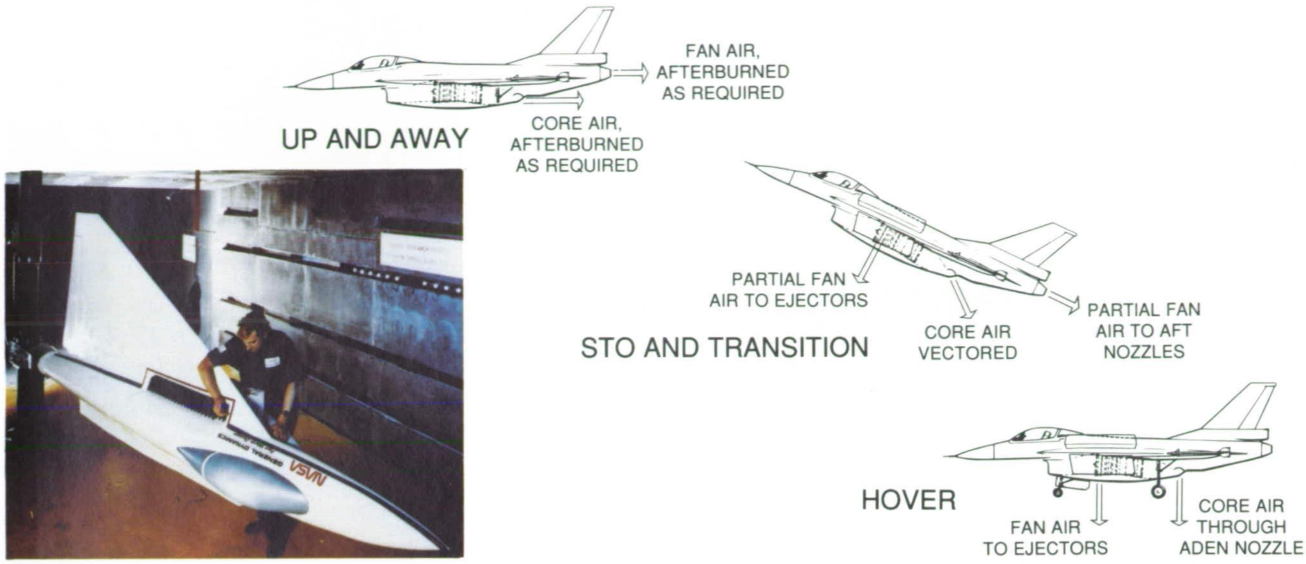


***Figure 4-4**.– NASA/Navy/General Dynamics one-third-scale powered ejector augmentor model.*

***Figure 4-5**.– Control force/moment generators.*

includes the use of a large-scale generic aircraft model, several small-scale models, and a full-scale, concept-specific, powered model. A General Dynamics one-third-scale powered ejector-augmentor model is shown in figure 4-4 (ref. 40).

Flight-control issues for the conceptual aircraft that incorporate these propulsion system arrangements center on (1) the generation of control forces and moments by the aerodynamic surfaces and propulsion effectors, including their interactive contributions; (2) stability and control characteristics of the configurations, particularly as they influence the requirement for control authority in the powered-lift and maneuvering-flight portions of the operational envelope; and (3) the integration of the aero/propulsion controls to enable precise control with modest pilot effort during transition, STOVL and low-speed flight, and for maneuver enhancement. Different arrangements of control effectors are presented by each configuration, as are concerns for their actual implementation. As shown in figure 4-5 vectored-thrust systems provide the capability for differential thrust deflection that may be used for pitch trim in transition and STOVL, and conceivably for yaw control as well. The ejector augmentor introduces the prospect of modulating and deflecting the flow from the augmentor for force and moment control.

Specifically, flow modulation would be used for pitch and heave control, and flow deflection could assist yaw control in STOVL and acceleration and deceleration during transition and low-speed flight. The ability to adjust flow volume and direction with the quick response required of primary flight control is the major uncertainty for this control method.

For the tandem fan, the ability to modulate and deflect the front fan flow is crucial to control that configuration. Variable-inlet guide vanes are a means of achieving rapid modulation of thrust from this section of the propulsion system. Flow deflection can be accomplished using vectoring nozzles similar to those used for vectored thrust. Differential thrust modulation between the front and rear nozzles would be used for pitch control while coordinated modulation of thrust from both nozzles would provide heave control. Differential fore and aft deflection affords a means for pitch control in transition, and the ability to vector the combined thrust of both nozzles is the key to achieving substantial acceleration and deceleration capability in transition. The remote augmenting lift system provides similar capability for modulating thrust and flow deflection from the front nozzle, which would be used for pitch and heave control in a manner similar to that used by the tandem-fan configuration. The feasibility of deflecting the front nozzle flow adequately is crucial for achieving good acceleration and deceleration through transition.

To some extent, all configurations share the need to rely on reaction controls during STOVL and low-speed flight. Whatever the requirement for reaction control, engine bleed flow is the primary source for this control system, and the ability to extract sufficient airflow from an engine intended for supersonic flight may pose significant limitations on reaction-control capability. Another potential for control shared by these concepts for maneuvering at transonic speeds is associated with the ability to deflect the aft nozzle flow for pitch and yaw control. Front nozzle flows may also be used in this manner to supplement pitch control for some configurations. For yaw control, the means for producing lateral thrust deflection must be achieved successfully. Finally, for the ejector augmentor, tandem fan, and remote augmenting systems, the problem of switching propulsion system flow from the front to the rear nozzles during the transition to or from powered-lift flight is considerable. This switching must to a large extent be free of transients that would introduce any large force or moment perturbations to the aircraft. Mechanical design of the hardware to accomplish this switching will be a significant challenge. To understand potential benefits and problems associated with each of these particular force and moment controls, control requirements studies must be conducted for each configuration, and powered-model wind tunnel tests at small and large scale and propulsion system component tests must be conducted.

Stability and control characteristics common to all configurations that must be established include pitch stability and trim, lateral trim, and directional stability. The issue of stability is not one of achieving adequate levels of positive stability in the basic airframe to ensure good flying qualities; through STOVL and transition, control-augmentation systems will be used to produce fully satisfactory flying qualities in these flight regimes. Rather, the issue is one of identifying and obtaining the appropriate level of stability, positive or negative, that will minimize the control authority required for trim, stabilization, and maneuvering associated with the mission phase. Combat maneuvering as well as powered-lift

flight regimes must be evaluated. For the ejector augmentor concept, it is also important to minimize ram drag to improve flightpath and speed controllability through transition. Powered-model tests will be used to address these concerns.

For all concepts, to achieve the operational capability in adverse weather at austere land-based sites or aboard ship, it will be necessary to provide the appropriate control-augmentation modes to yield precise control and satisfactory flying qualities (see refs. 20 and 21). Specifically, attitude stabilization and translational velocity command (independent of attitude control in the longitudinal and vertical axes) should be provided through integration of the combined aerodynamic and propulsion system controls for transition and STOVL. At conditions for high-speed maneuvering, rapid and precise attitude control and good normal and axial acceleration control will be the important contributions of the array of control effectors. Representative combinations of propulsion controls for each concept are shown in figure 4-6. Design studies are required to deal with the specific capabilities of each type, and piloted simulation evaluations must be performed to obtain a realistic assessment of the actual operational capability that can be expected to result from each particular concept.

A major R&T activity that was recently initiated is a joint program between the United States and the United Kingdom to advance technology for supersonic, advanced STOVL (ASTOVL) concepts (ref. 41). The Memorandum of Understanding (MOU) between the two countries, signed in 1986, states that the development of technology will include a collaborative ground-based research program on single-engine ASTOVL aircraft/propulsion system concepts over a span of about 5 yr. The U.S./U.K. supersonic ASTOVL technology program includes contractual aircraft, and propulsion-system conceptual design studies of the four supersonic STOVL concepts previously described, a common technology program, and a concept-specific technology program. Further description of the design studies and the technology programs follows.

The conceptual design studies were effective in the early portion (i.e., 1986-1988) of the U.S./U.K. program for identifying technology developments and assessing the potential of the several supersonic ASTOVL concepts of interest. Each government conducted, independently, complete analyses of all four concepts. The aircraft conceptual design studies were based on a Technology Availability Date (TAD) of 1995. The 1995 TAD for the aircraft is defined as the

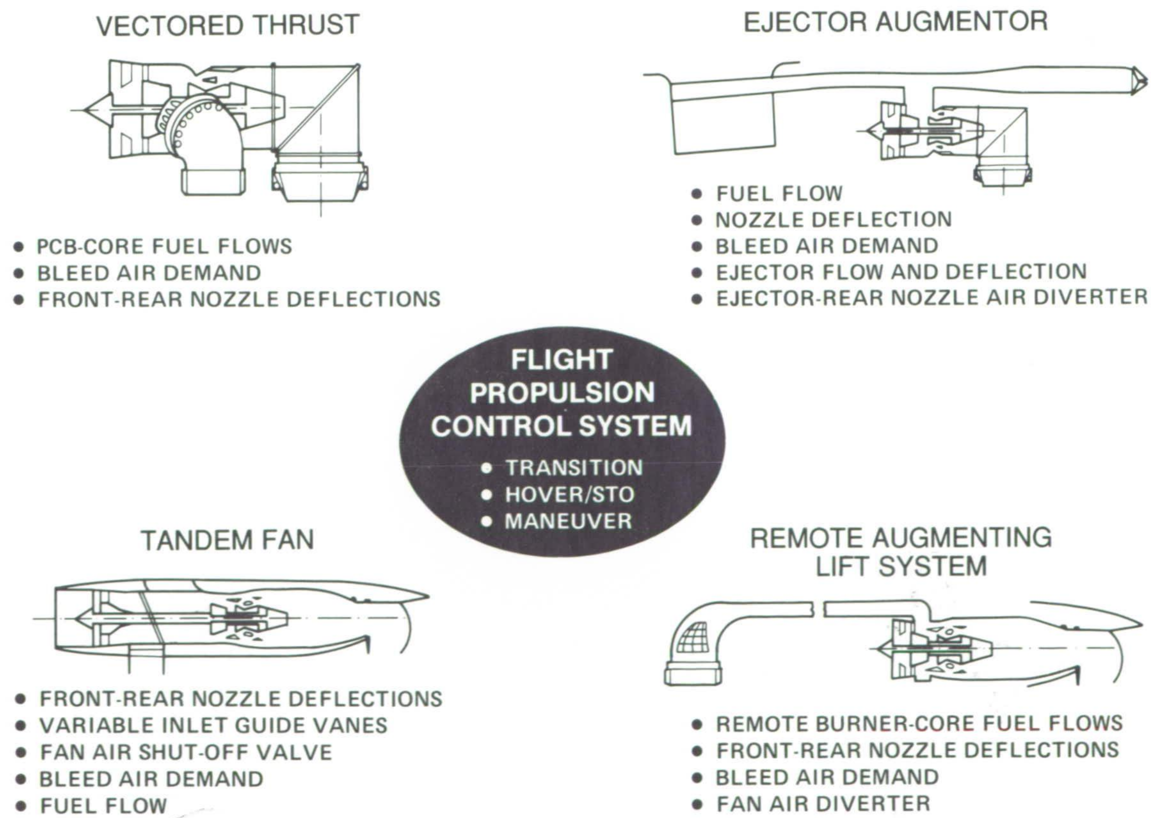


Figure 4-6. *– Flight-propulsion controls.*

time at which technology has been demonstrated to enable full-scale development to begin in 1995. A 1995 TAD for the engine is defined as that technology which has been demonstrated in component and/or engine ground tests and which the government would be confident to include in a new, full-scale engine development beginning in 1995. Following the contractual studies by the engine and airframe manufacturers, the governments will conduct an assessment intended to eliminate one or more concepts and identify those which should be investigated in the technology programs.

The common technology program consists of technologies which are applicable to all, or most, of the supersonic ASTOVL concepts. Common technology program elements include hot-gas ingestion; fan stream burning; jet plume/aircraft structure interactions; environmental effects; and integration of flight/propulsion controls. Activities for some of these common technology elements were initiated in early 1987.

The concept-specific technology program is in the early planning phase. Definition for much of the program is dependent upon results from the design studies and common technology program. Program initiation follows the assessment effort that includes identification of a reduced number of concepts that are most promising for further development. The concept-specific technology program for selected concept(s) will concentrate upon critical areas of deficiency to bring the selected concept(s) to the point at which a flight demonstrator/research aircraft study could be embarked upon with a high degree of confidence.

As previously stated, the U.S./U.K. MOU authorizes only a ground-based research program over the 1986-1990 timeframe. However, as stated in the initial press release of February 10, 1986, the two governments envision the possibility of undertaking a joint experimental aircraft activity that could lead to the production of new-generation ASTOVL aircraft, should there be a requirement for such aircraft. If the joint work is undertaken, it will be covered by separate agreements.

SUMMARY

STOVL aircraft technology is on the threshold of expansion. There is a potential need for fighter aircraft that feature STO; vertical landing; associated enhanced in-flight characteristics, particularly in subsonic regimes; and supersonic capability. The cost for STOVL, compared to STOL or CTOL, continues to decrease. Supersonic fighters have thrust-to-weight ratios greater than one as required for vertical flight. Advancing technology continues to increase the propulsion system thrust-to-weight ratio and to decrease the structural weight fraction. STOVL fighters that feature significant dash capability to supersonic speed could be introduced soon after the turn of the century. With time, the marriage of sustained supersonic cruise and STOVL is also inevitable.

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